Plants in Space Biology, pages 207-216

In: H. Suge (ed.) Plants in Space Biology. 1996.

GAS BALANCE IN A PLANT-BASED CELSS

Raymond M. Wheeler

NASA Biomedical Operations and Research Office, Kennedy Space Center, FL 32899, USA

INTRODUCTION

The concept of using plants for atmospheric regeneration in controlled ecological life support systems (CELSS) has been studied since the early 1950s, and most likely discussed long before this (Myers 1954, Krall and Kok 1960, Golueke and Oswald 1964). Indeed, Priestley (1772) demonstrated metabolic reciprocity between plants and heterotrophs over 200 years ago. The basis for using plants in closed life support systems is the process of photosynthesis, in which carbon dioxide is fixed enzymatically to form carbohydrate (biomass) while oxygen is released. A simplified version of the reaction can be written as:

$$CO_2 + H_2O \xrightarrow{light} CH_2O + O_2$$

where CH_2O represents a single-carbon unit of carbohydrate.

Most early studies of photosynthetic atmospheric regeneration focused on algae, e.g., *Chlorella* (Krall and Kok 1960, Golueke and Oswald 1964, Eley and Myers 1964), because of their high photosynthetic productivity and ease of culture. However, recent studies have shown that higher plants have photosynthetic productivities nearly as high as algae (Bugbee and Salisbury 1988, Wheeler *et al.* 1993, 1996), and advances in controlled environment agriculture have refined techniques for intensive production systems with higher plants (Resh 1989). These developments, coupled with the difficulties of incorporating algae into the human diet, brought about a refocusing of CELSS work toward higher plants in the 1980s (Golueke and Oswald 1964, MacElroy and Bredt 1985). Because the issue of edible biomass (food) is critical to CELSS, it is likely that higher plants would have a major role in any bioregenerative life support system; therefore, I will focus my discussion on higher plant systems, although it should be borne in mind that the optimal combination of photosynthetic organisms for a CELSS is still unresolved.

MEASURING PLANT GAS EXCHANGE

Plant gas exchange (photosynthesis, respiration, and transpiration) rates have been measured for many years using a variety of techniques (Coombs *et al.* 1985). Typically, these measurements use single leaves in conjunction with portable or bench-top gas exchange units with transparent cuvettes (Coombs *et al.* 1985). Whole plant photosynthesis can be estimated from single leaf rates, provided total leaf area and amount and distribution of intercepted light are known. However, extrapolating from single leaves to whole plants or stands of plants carries a high degree of uncertainty. (By stands, I refer to all shoot structures, as well as roots and their associated microflora).

For CELSS studies, measurements of whole stand gas fluxes are most useful, but this requires enclosing the entire stand in a chamber (Gerbaud *et al.* 1988). As with single leaves, stand gas fluxes can be measured using two general approaches: closed or open systems (Coombs *et al.* 1985, Mitchell 1992). In closed systems, changes in gas concentration, typically carbon dioxide (CO_2), are tracked over time (Coombs *et al.* 1985, Wheeler 1992). These changes can be converted to absolute quantities if the system volume and leakage rate are known. A variation of the closed system is the semi-closed or null-balance approach, where the amount of CO_2 needed to hold a constant set point during the light is measured (Coombs *et al.* 1985, Mitchell 1992). In practice, controlled environment systems with plants that are atmospherically closed require a null-balance mode of operation to prevent CO_2 depletion. In contrast to closed systems, open systems are ventilated to their external environment, but the CO_2 concentrations of incoming and outgoing air streams are carefully measured (Bugbee 1992, Mitchell 1992). In open systems, chamber volume and leakage are not critical measurements (provided leakage is outward), but gas flow through the system must be measured accurately (Coombs *et al.* 1985, Bugbee 1992). In theory, both approaches also can be used to track stand O_2 exchange, yet difficulties in measuring concentration changes against large background O_2 levels (e.g., 21%) make these measurements more difficult.

OBSERVATIONS FROM NASA'S BIOMASS PRODUCTION CHAMBER

At Kennedy Space Center, FL, a series of plant studies have been conducted with a large, closed chamber for NASA's CELSS program. The chamber, called the Biomass Production Chamber, provides 20 m^2 of growing area, with an internal volume (including air ducting) of 113 m^3 (Prince *et al.* 1987, Wheeler 1992). Lighting is provided with 96 400-W high-pressure sodium lamps, air circulation with two 30-kW blowers, and heat rejection with two 52-kW chilling systems. Further details on the chamber design and capabilities can be found in Prince *et al.* (1987), Sager *et al.* (1988), and Wheeler (1992).

Gas exchange of plant stands in the chamber is measured by tracking diurnal changes of concentration in response to lighting cycles (closed system measurements) or by monitoring the amount of CO_2 added to hold a set-point during the light period (semi-closed measurements). When the chamber is filled with plants, CO_2 concentrations drop quickly in the light until a set-point is reached, at which CO_2 is added from an external source (Fig. 1). During the dark cycle, no external CO_2 is needed and chamber CO_2 concentrations rise from plant respiration. In contrast to CO_2, O_2 increases during the light and decreases during the dark (Fig. 1). If no steps are taken to remove or control O_2, concentrations will continue to increase as the plants grow. In an operating CELSS, O_2 produced by the plants would be used by the humans, while CO_2 from the humans would be used by the plants. For our studies, we either ventilate (open) the chamber or engage molecular sieve

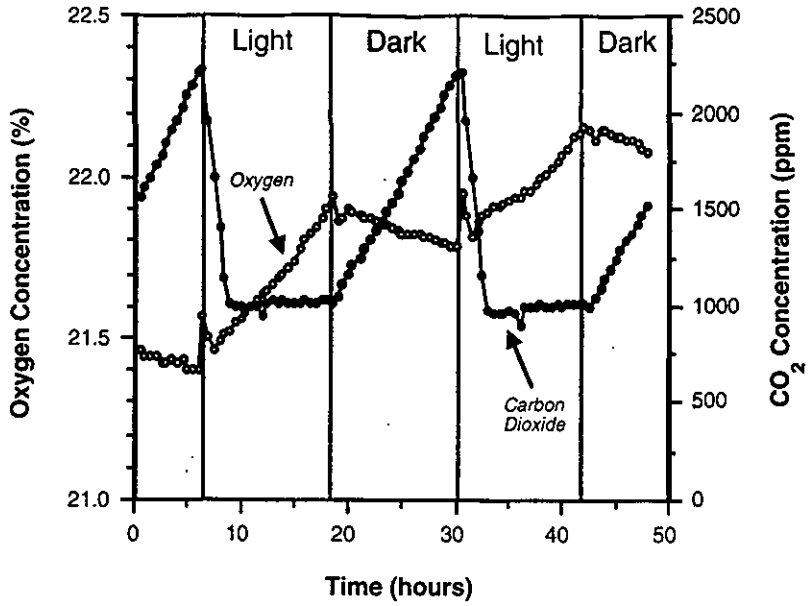

Fig. 1 Change in carbon dioxide (CO_2) and oxygen (O_2) concentrations in a closed chamber in response to 12-h light/dark cycles during growth of a soybean crop. When CO_2 dropped to 1000 ppm in the light, CO_2 was added from an external supply to maintain the 1000 ppm set-point. The chamber provided 20 m^2 of growing area with an atmospheric volume of 113 m^3.

scrubbing systems to prevent excessive O_2 build-up. (Interestingly, this becomes a necessity to prevent fire hazards when O_2 concentrations exceed 25%.)

By calculating an average CO_2 exchange rate each day, one can track the gas exchange throughout growth and development of a crop (Fig. 2). This allows a running calculation of total CO_2 fixed and hence an estimate of standing biomass. The gas exchange measurements also provide a diagnostic check on the plant stand's general health and metabolic status, as well as a rapid indicator of environmental perturbations. For example, the effect of an unscheduled high temperature episode during the dark period (day 56) is apparent as a sharp increase in respiration of a soybean stand (Fig. 2). Another example is evident from the high light curve (Fig. 2), where a decrease in the photosynthetic rate occurred between days 30 and 50. This coincided with a collapse (i.e. lodging) of the soybean stand, which caused gaps in the canopy and incomplete light interception. It is noteworthy that this lodging caused nearly 10% loss in potential net photosynthesis throughout the growth cycle! A lag in CO_2 uptake also is apparent early in growth (Fig. 2). For these studies, fixed spacing was used throughout growth; consequently, growing space and lighting were wasted when plants were young. This could have been reduced by starting seedlings in a separate area and then transplanting the seedlings to the final production area, or by utilizing an adjustable spacing system. For crops such as lettuce, potato, and soybean, transplanting could save perhaps 10 to 12 days of use in the final production area, resulting in substantial increases in system productivity (Wheeler *et al.* 1996).

When one considers management of plant

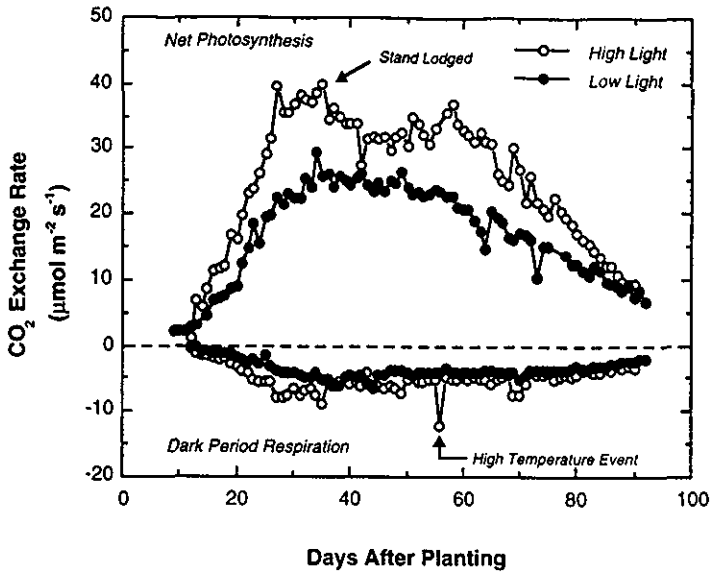

Fig. 2 Carbon dioxide (CO_2) exchange rates during light (net photosynthesis) and dark cycles (dark period respiration) throughout growth and development of two soybean crops. Plants were grown at 815 μmol m^{-2} s^{-1} (high light) and 480 μmol m^{-2} s^{-1} (low light) PPF. Many deviations of data from the curves represent responses to environmental events, e. g., high respiration as a result of chamber overheating on day 56 of the high light study. An apparent dip in the high light photosynthesis curve occurred near day 30 (lasting until day 50), which coincided with a collapse (lodging) of the stand. Full ground cover was reached near 30 days.

systems for a CELSS, successive "batch" plantings would result in oscillations of gas exchange throughout growth (Fig. 2). A more likely scenario would involve the use of staggered plantings to damp oscillations in system gas fluxes and maintain a constant supply of O_2 and food (Drysdale *et al.* 1992, Stutte and Sager 1995) (Fig. 3). This could in turn reduce food and gas storage requirements. A potential disadvantage of staggered plantings is that they might require simultaneous culture of plants of different ages in a common environment (e.g., similar lighting, temperature, and humidity), which may not be optimal for a specific stage of development.

In most controlled environment studies with plants, light (photosynthetic photon flux-PPF) is a primary limiting factor for photosynthesis (Fig. 4); consequently, CELSS designs and energy requirements are directly affected by plant lighting (Drysdale *et al.* 1994, Wheeler *et al.* 1996). In contrast to single leaves, instantaneous photosynthetic rates for some stands do not saturate, even at relatively high PPFs (Fig. 4) (see also, Bugbee and Salisbury 1988). In addition, light compensation points (point where net CO_2 uptake=0) are typically higher for stands than single leaves, because of their high background respiration rates of stands. In our studies, light compensation typically occurred near 200 μmol m^{-2} s^{-1} PPF when plants were grown at 600 to 800 μmol m^{-2} s^{-1}. In studies with wheat grown at much higher PPF (2,000 μmol m^{-2} s^{-1} for 20- or 24-h photoperiods), standing biomass was much greater and light compensation points were as high as 600 μmol m^{-2} s^{-1} (Bugbee 1992). Whether stands of dicots with horizontal leaf architectures could tolerate such high irradiance continuously seems doubtful, but

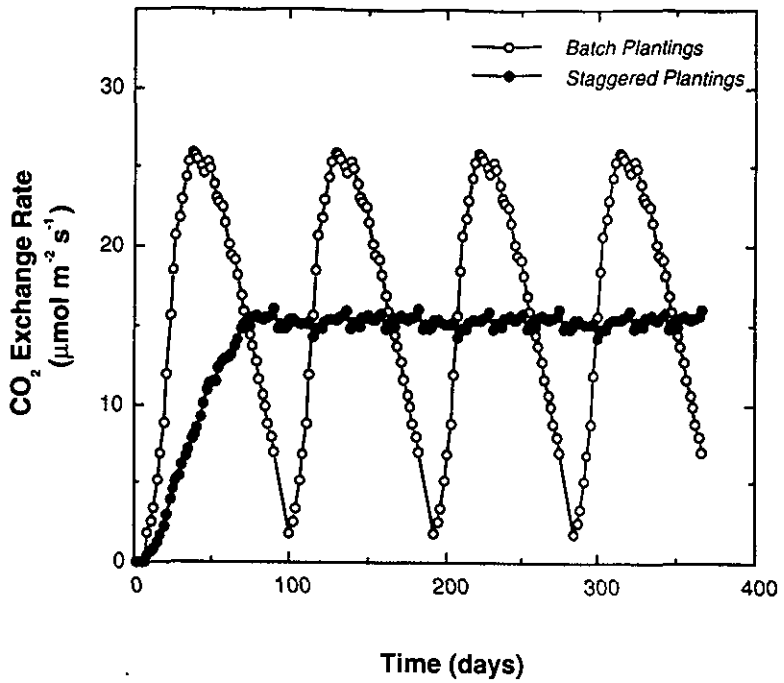

Fig. 3 Estimated carbon dioxide (CO_2) uptake rates from photosynthesis of a soybean stand (see Fig. 2) using sequential batch plantings (all plants started at one time and then harvested at one time) versus staggered plantings (one fourth of the area planted and harvested at equally spaced intervals).

should be studied for CELSS. Related studies with potato suggest that photosynthesis and growth may not increase much once an upper limit of total daily irradiance is reached (Stutte *et al.* 1996).

CO_2 concentration also can be used to control the rate of gas exchange by plants, and in practice, CO_2 concentration is easily optimized with little additional system expense. Maximum photosynthetic rates for the C_3 species tested in our system were reached between 1,000 and 2,000 ppm (0.1 to 0.2 kPa) (Wheeler *et al.* 1993, 1994, 1996). Unlike light compensation, CO_2 compensation points are relatively similar between single leaves and whole stands (50–100 ppm), provided chamber air mixing is adequate (Wheeler *et al.* 1993).

GAS BALANCES IN A CELSS

The best results from our studies to date (PPF levels up to 55 mol m^{-2} day^{-1}) suggest that about 20 m^2 of planted area would be required to provide minimal O_2 requirements and CO_2 removal needs for one person (Wheeler *et al.* 1996). This assumes a resting rate or low level of metabolic activity for humans, and would need to be increased if average levels of activity were higher (Doerr *et al.* 1995, Mitchell *et al.* 1996). But as noted earlier, the required area of plants also depends on lighting capacity of the system. Any imbalances in CO_2 and O_2 fluxes between plants and humans also should be considered for a CELSS (Krall and Kok 1960, Eley and Myers 1964). Assimilation quotients (CO_2 fixed: O_2 produced) of plants are generally close

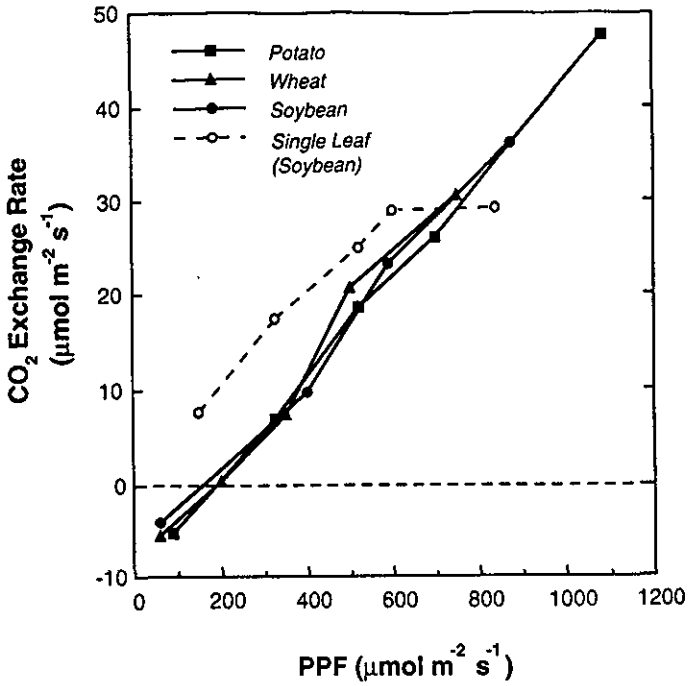

Fig. 4 Carbon dioxide (CO_2) exchange rate of plant stands in response to changes in photosynthetic photon flux (PPF). Measurements were taken soon after full ground cover for stands grown with ~700 μmol m^{-2} s^{-1} PPF. A typical single leaf curve (hatched line) is superimposed, showing the lower saturation level and lower light compensation point (projected) in comparison to whole stands.

to 1.0, whereas respiratory quotients (CO_2 produced: O_2 used) of humans are near 0.8 (Rabinowitch 1945, Krall and Kok 1960). Such imbalances might be minimized by changing the proportion of fat- and carbohydrate-producing plants, or by modulating the forms of nitrogen provided to the plants (Krall and Kok 1960). For example, assimilation quotients for some algae are lower when they are grown with nitrate versus ammonium or urea; however, this phenomenon has not yet been demonstrated for higher plant communities. Alternatively, CO_2: O_2 ratios might be adjusted with supplementary physical-chemical systems thereby avoiding the need for precise biological balance.

In a totally closed CELSS where plants are used both for food and atmospheric regeneration, fluxes of O_2 and CO_2 are also affected by waste recycling. To demonstrate this, let us assume the following: 1) all plant biomass and food cycle through the system as carbohydrate (CH_2O); 2) half of the biomass produced is edible, i.e., harvest index=0.5 (this seems a reasonable average for a range of crops studied for CELSS; Wheeler *et al.* 1996); and 3) all the human waste and inedible plant biomass are recycled back to CO_2 and H_2O. In such a scenario, two units of total biomass must be produced to supply one unit of food and one net unit of O_2 (Fig. 5). Using the data from our studies at Kennedy Space Center, this translates to a requirement of 40 m^2 of planted area per person (Wheeler *et al.* 1996). Note that recycling carbon from the inedible biomass and other

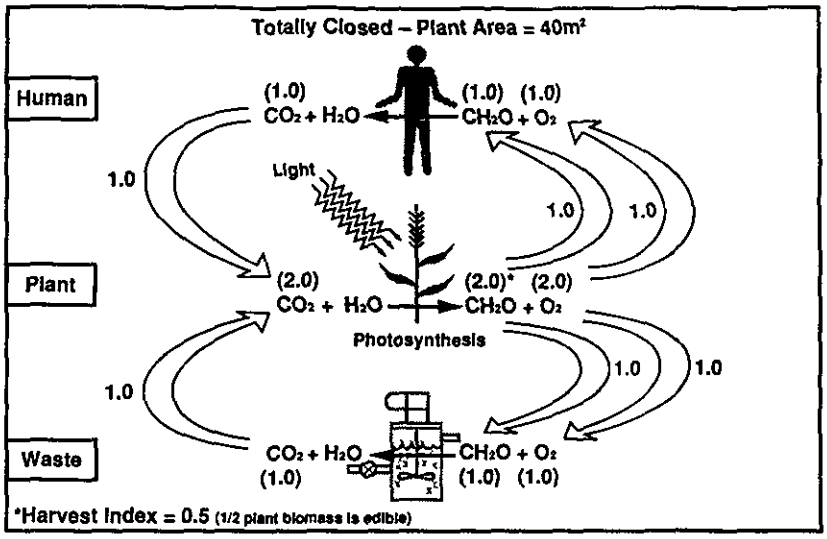

Fig. 5 Model of carbon and oxygen fluxes in a CELSS including a human habitat, a plant producing module, and a waste treatment system. The model assumes all the fixed carbon is in the form of carbohydrate (CH_2O), CO_2 and O_2 fluxes in photosynthesis and respiration are exactly 1 : 1 (see text for discussion of assimilation and respiration quotients), and half of the plant biomass is edible (i.e., harvest index = 0.5). Waste treatment is shown only for inedible plant biomass, but would also be required for human waste to provide complete conversion to CO_2. To provide 1.0 unit of edible CH_2O to feed one human, 2.0 units of total biomass must be produced, requiring 40 m^2 of plant growing area.

waste in the system requires a full unit of O_2, after which the CO_2 is returned to the photosynthetic module.

If a portion (0.1 CH_2O unit) of the waste biomass could be converted to food through use of organisms such as fish or fungi (Strayer 1993, Finger and Strayer 1994), the total area for the photosynthetic module can be reduced by 10% to 36 m^2 per person (Fig. 6). System O_2 production and CO_2 fixing requirements also would drop proportionately, since less waste recycling is required. This demonstrates the importance of cycling a high proportion of biomass through the system as food. However, adding secondary conversion steps with fish or fungi cultivation would increase system complexity, and these costs and reliabilities would need to be evaluated against gains accrued from reduced growing area and lighting for plants (Drysdale *et al.* 1992, 1994).

A more direct way of cycling proportionately more biomass through the food loop is to increase the harvest index of the plants. Increasing the harvest index from 0.5 to 0.6 would require total production of only 1.7 units of CH_2O to provide 1.0 unit of food to the humans (with no food retrieved from waste treatment), thereby decreasing the required plant area 15% to about 33 m^2 per person.

The intent of these models is to give a simplified view of carbon and oxygen fluxes through a CELSS, but clearly the systems would be more complex. For example, food estimates are based solely on a dietary energy need of 2800 kcal per person per day, and take no accounting for protein, fat, vitamin, and micronutrient requirements. In addition, at least some treatment of human waste would be required to recycle water and sustain some of the CO_2 needs of the plants, and this is not shown. In a more sophisticated CELSS, recycling schemes for other elements (e.g., N) must also be considered in

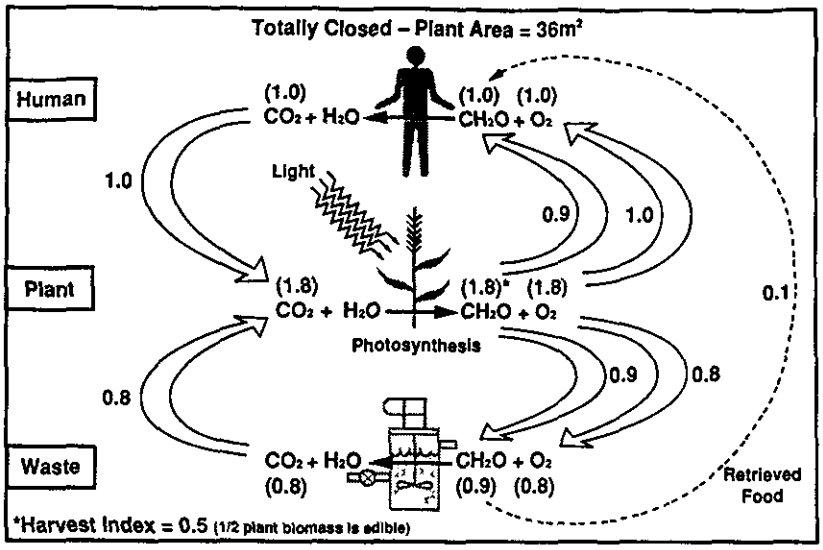

Fig. 6 Model of carbon and oxygen fluxes in a CELSS given the same assumptions as in Fig. 5, but in this case 0.1 units of CH_2O are retrieved from waste as food. This might be accomplished by processing waste biomass using fungi or fish. The net effect is a 10% decrease in the plant area (40 m^2 to 36 m^2) required to support one human.

terms of resupply costs and feasibility. Recent studies have shown that biological degradation of inedible biomass can efficiently retrieve a large portion of the nutrients (e.g., N and K) needed to grow subsequent generations of plants (Finger and Strayer 1994, Mackowiak *et al.* 1996), and similar approaches should work with human wastes, although further testing is needed. An interesting challenge looming for CELSS research will be dealing with large discrepancies in Na and K requirements between humans and plants. Additionally, if a CELSS is to be employed in a weightless environment, one must consider any effects of microgravity on photosynthesis and overall plant growth and development (Brown *et al.* 1996).

In all probability, early attempts at a CELSS will be only partially closed, and substantial amounts of food, O_2, and other consumables will be imported. If one approaches mass balances from this perspective, very different scenarios arise: If, for example, half the food is imported and half the food is produced in the CELSS, the entire atmospheric regeneration can be met with only half the area of plants (i.e., 20 m^2 per person), provided waste CH_2O recycling is minimized (Fig. 7). By disposing of or storing a large portion of organic wastes, most of the O_2 from the photosynthetic system can be sent to the humans and the CO_2 removal needs reduced proportionately. Imported food could then offset elements discarded in waste and help satisfy more demanding aspects of the human diet (Mitchell *et al.* 1996). Meanwhile, the waste biomass could be stored as a future resource (e.g., carbon supply) as the system becomes more autonomous.

SUMMARY

The use of plants for O_2 production, food production, and CO_2 removal in life support systems holds great promise. By tracking rates of photosynthesis and respiration of the plants, the effects of environmental management on system gas balances can be assessed rapidly. In any

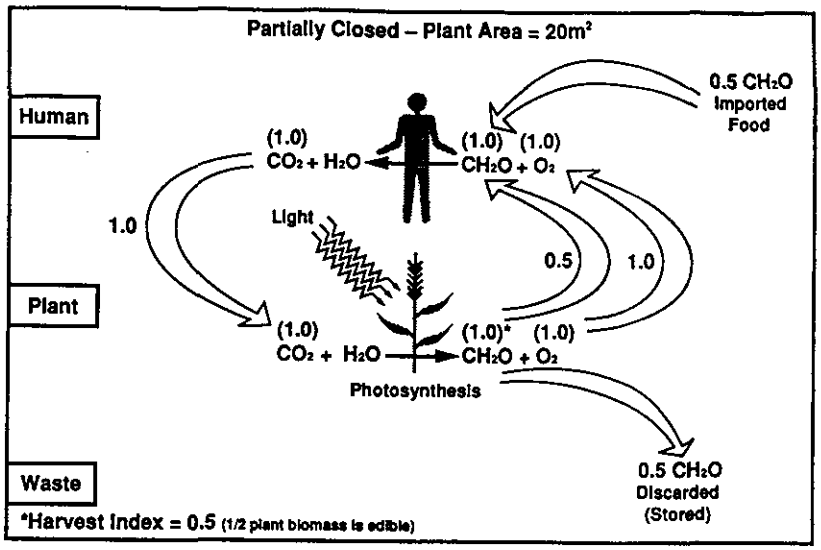

Fig. 7 Model of carbon and oxygen fluxes in a partially closed CELSS, where 0.5 units of waste CH_2O are discarded or stored. In this case, all the O_2 and CO_2 removal needs and half of the food for one human can be provided by 20 m^2 of plants. The remainder of food is provided by stowage (imported).

CELSS, lighting is a primary limitation for photosynthesis and consequently a critical design consideration. Management of gas balances in a plant-based CELSS also must consider waste management strategies and the degree of system closure. In all cases, plants with a high harvest index (i.e., high proportion of edible biomass) are highly desirable, to maximize carbon cycling through the human food chain.

Acknowledgments—I wish to acknowledge the contributions and dedication of all my co-workers at Hangar L and the CELSS Breadboard Project at Kennedy Space Center, Florida, USA.

REFERENCES

Brown, C.S., Tripathy, B.C., Stutte, G.W. 1996. This book.

Bugbee, B. 1992. *HortScience* 27: 770-776.

Bugbee, B. 1992. *Advances in Space Research* 12(5): 85-95.

Bugbee, B.G., Salisbury, F.B. 1988. *Plant Physiology* 88: 869-878.

Bugbee, B.G., Salisbury, F.B. 1989. *Advances in Space Research* 9(8): 5-15.

Coombs, J., Hall, D.O., Long, S.P., Scurlock, J.M.O. (eds.). 1985. *Techniques in bioproductivity and photosynthesis*. Pergamon Press, Oxford, UK.

Doerr, D.F., Convertino, V.A., Blue, J., Wheeler, R.M., Knott, W.M. 1996. *Acta Astronautica* (in press).

Drysdale, A., Thomas, M., Fresa, M., Wheeler, R. 1992. *SAE Technical Paper 921241*, Soc. Automotive Eng., Seattle, WA, USA, July 13-16, 1992.

Drysdale, A.E., Dooley, H.M., Knott, W.M., Sager, J.C., Wheeler, R.M., Stutte, G.W., Mackowiak, C.L. 1994. *SAE Technical Paper 941292*, Soc. Automotive Eng., Friedrichshafen, Germany, June 20-23, 1994.

Eley, J.H., Myers, J. 1964. *Texas Journal of Science* 16: 296-333.

Finger, R.W., Strayer, R.F. 1994. *SAE Technical Paper 941501*, Soc. Automotive Eng., Friedrichshafen, Germany, June 20-23, 1994.

Gerbaud, A., Andre, M., Richaud, C. 1988. *Physiolgia Plantarum* 73: 471-478.

Golueke, C.G., Oswald, W.J. 1964. *Annual Review of*

Plant Physiology 15: 387-408.
Krall, A.R., Kok, B. 1960. *Developments in Industrial Microbiology* 1: 33-44.
MacElroy, R.D., Bredt, J. 1985. *NASA Conference Publication* 2378.
Mackowiak, C.L., Garland, J.L., Strayer, R.F., Finger, B. W., Wheeler, R.M. 1996. *Advances in Space Research* 18(1/2): 281-287.
Mitchell, C.A. 1992. *HortScience* 27: 764-767.
Mitchell, C.A., Dougher, T.A.O., Nielsen, S.S., Belury, M.A., Wheeler, R.M. 1996. This book.
Myers, J. 1954. *Journal of Aviation Medicine* 25: 407-411.
Priestley, J. 1772. *Philosophical Transactions of the Royal Society, London* 62: 147. *Cited in*: Rabinowitch, E.I., 1945, Interscience Pub. Inc., New York, NY, USA.
Prince, R.P., Knott, W.M., Sager, J.C., Hilding, S.E. 1987. *SAE Technical Paper 871437*, Soc. Automotive Eng. Conf., Seattle, WA, USA, July 1987.
Rabinowitch, E.I. 1945. *Photosynthesis and related processes*. Interscience Pub. Inc., New York, NY, USA.
Resh, H.M. 1989. *Hydroponic food production*. Woodbridge Press Pub. Comp., Santa Barbara, CA 93160 USA.
Sager, J.C., Hargrove, C.R., Prince, R.P., Knott, W.M. 1988. *ASAE Paper 88-4018*, Amer. Soc. Agr. Eng., St. Joseph, MI, USA.
Strayer, R.F. 1993. *SAE Technical Paper 932253*, Soc. Automotive Eng., Colorado Springs, CO, USA, July 12-15, 1993.
Stutte, G.W., Sager, J.C. 1995. *ASAE Paper No. 955654*. Amer. Soc. Agr. Eng., St. Joseph, MI, USA.
Stutte, G.W., Yorio, N.C., Wheeler, R.M. 1996. *Journal of American Society for Horticultural Science* 121: 264-268.
Wheeler, R.M. 1992. *HortScience* 27: 777-780.
Wheeler, R.M., Corey, K.A., Sager, J.C., Knott, W.M. 1993. *Crop Science* 33: 161-168.
Wheeler, R.M., Mackowiak, C.L., Sager, J.C., Yorio, N. C., Knott, W.M., Berry, W.L. 1994. *Journal of American Society for Horticultural Science* 119: 610-615.
Wheeler, R.M., Mackowiak, C.L., Stutte, G.W., Sager, J. C., Yorio, N.C., Ruffe, L.M., Fortson, R.E., Dreschel, T.W., Knott, W.M., Corey, K.A. 1996. *Advances in Space Research* 18(4/5): 215-224.